ASSOCIATIONS BETWEEN SOCIOECONOMIC STATUS AND EEG ALPHA POWER IN MONOLINGUAL AND BILINGUAL INFANTS: EARLY PREDICTORS OF NEURAL PROCESSES UNDERLYING EXECUTIVE FUNCTION

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Abstract

Research suggests that the bilingual experience facilitates development of executive function (EF) skills, whereas experiencing low socioeconomic status (SES) has been associated with challenges to EF. Little research, however, has explored how SES contributes to variation in neural processes underlying EF during infancy, nor how SES and bilingualism interact to predict neural processes underlying EF. This study tested bilingual and monolingual exposed infants from low- to mid-SES backgrounds (n = 116) when they were 2, 6, 9, and 12 months of age to explore variation in an early neural predictor of EF - frontal alpha power. Results demonstrated that SES variables predicted alpha power at both 9 and 12 months. Minimal differences in alpha power were observed between bilingual and monolingual-exposed infants. However, language group did moderate associations between SES and alpha power at 9 months, such that negative associations between SES and frontal alpha were observed for the monolingual, but not bilingual group. Results suggest that SES contributes to variation in neural processes underlying EF from infancy, and that bilingualism might act as a protective factor for early development of EF.

Keywords: bilingualism, executive function, socioeconomic status

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Associations between socioeconomic status and alpha power in monolingual and bilingual infants: Early predictors of neural processes underlying executive function

Executive functions (EF) are defined as a set of mental processes including working memory, inhibitory control, and cognitive flexibility (Fiske & Holmboe, 2019). These skills are necessary for many types of more complex cognitive behaviour, including critical thinking, problem-solving, and memory. Some variation in EF development is thought to stem from experience-driven modifications to neurodevelopment during infancy and early childhood (e.g., Thompson & Steinbeis, 2020), however sources of early variation are less well understood. One contributor to variation in the early environment is low socioeconomic status (SES), which has been associated with challenges in the development of EF. For example, experiences such as high levels of stress and poverty have been found to negatively predict EF scores from as early as 6 months of age (Clearfield & Niman, 2012; Hackman et al., 2015). In contrast, a large body of evidence has suggested that bilingualism, the use of two languages, is associated with some advantage in the development of EF. Many studies that have compared bilingual and monolingual individuals on EF-related tasks have found better performance by bilingual language learners, even from infancy (for recent reviews see Antoniou, 2018; Gunnerud et al., 2020). Advantages are thought to arise, in part, because the bilingual experience involves the unique set of experiences, or application of skills, that are relevant to hearing and using more than one language (Bialystok, 2012). Some accounts have suggested that EF skills such as inhibition and cognitive control are required in situations where bilinguals need to inhibit the language that is not being used in a given context to produce the language that is (e.g., Bialystok, 2012). More recent accounts suggest that, from infancy, the particular demands of a bilingual environment might lead to adaptation of the attention system – in particular an executive attention capacity that reflects interactions between attention and working memory systems (Bialystok, 2017). Moreover, the experience of bilingualism might shape early attention patterns in a manner that could contribute to EF development (e.g., Arredondo, Aslin, & Werker, 2022).

Notably, although experience-driven modifications to neurodevelopment are evident from the earliest stages of life, and although bilingualism is prevalent across SES strata, little research has explored a) associations between SES and neural predictors of EF during infancy, nor b) the interaction between SES and bilingualism on the development of EF. In the present study I will test these questions in a longitudinal sample of monolingual and bilingual infants from 2 - 12 months of age. First, I will review the literature describing (1) neurophysiological underpinnings of EF, (2) neural predictors of EF that might emerge during infancy, (3) associations between socioeconomic status and the development of EF, and (4) EF development in bilingual compared to monolingual language learners. I will also discuss (5) how factors such as SES and bilingualism might interact to differentially predict early neural correlates of EF.

Neurophysiological Measures of Executive Function

One way that neural processes underlying EF are measured during infancy and early childhood is by using electroencephalography (EEG). EEG reflects a summation of postsynaptic potentials generated from large groups of cortical neurons firing in synchrony (Davidson, Jackson, & Larson, 2000). EEG may not be a direct measure of neural activity, but it does provide information about the underlying function and organization of the brain, and it can be used to explore early developing attention abilities, predictors of EF abilities that emerge later in childhood, as well as neural processes underlying EF (Buzsáki et al., 2012, Pizzagalli, 2007).

One way to use EEG to measure infants' neural processing underlying EF is to record EEG during EF-related tasks and measure event-related potentials (ERPs). ERPs are short segments of EEG data, time-locked to particular events of experimental interest, and averaged over many trials. For instance, one study examined executive control in sixty-two 5-year-old children on a go/no-go task of inhibition, while event-related potentials (ERPs) were recorded (Barac, Moreno, & Bialystok, 2016). The participants were measured on a) interference suppression, or their ability to ignore salient perceptual information while attending to less salient conflicting information, and b) response inhibition, or their ability to inhibit actions that are inappropriate in a context, and which may interfere with goal-driven behaviour. This study found that bilinguals outperformed monolinguals in interference suppression and response inhibition by producing faster reaction times, and by exhibiting larger P3 amplitude and shorter N2 and P3 latencies, which were overall associated with better behavioural discrimination (Barac, et al., 2016).

Another way to use EEG to measure neural processes underlying EF is to decompose the EEG signal into relevant frequency bands. EEG is composed of distinct rhythms estimated in various frequency ranges (e.g., delta, theta, alpha, beta, and gamma), which are linked to different perceptual and cognitive processes. EEG power can be recorded during a task or at rest, and power in certain frequency bands is thought to be reflective of processes underlying various cognitive functions. For example, alpha power has been found to be associated with inhibition and other EF-related skills (Anderson & Perone, 2018, Camacho et al., 2020; Klimesch, 2012). Notably, research shows that greater baseline-to-task increases in frontal alpha power are correlated with greater inhibitory control performance (Bell, 2001, Watson & Bell, 2013).

Examining differences in EEG power between EF tasks and baseline has been used to understand neural correlates of EF during childhood. For example, Wolfe and Bell (2004) found that 4.5-year-old children displayed greater medial frontal power in the 6 to 9 Hz (alpha) frequency range during a task of inhibitory control (day-night Stroop task) compared to baseline. Notably this alpha power difference was larger for bilingual children in comparison to monolingual children (Wolfe & Bell, 2004). Increased task-related power in the alpha frequency range is thought to be associated with increased allocation of attention.

Baseline EEG Frontal Alpha Power

While recording EEG during EF tasks provides valuable information about neural development underlying EF, it is somewhat challenging to measure EF behaviourally in infants, who are not yet able to perform complex EF tasks. While much research has used eye-tracking technology to infer information about infants' developing EF abilities (Hendry, Jones, & Charman, 2016), it is also possible to examine early neural correlates of EF from resting, or baseline EEG, which does not require infants to perform any task at all. Studies exploring early neural predictors of EF from baseline EEG have frequently identified frontal alpha power as predictive of behavioural EF abilities during both infancy and early childhood. For example, 8-month-old infants who tolerated longer delays on a behavioural task measuring inhibitory control and working memory (Piaget's A-not-B task), had larger frontal EEG alpha power values at rest than infants who performed poorly on the task (Bell & Fox, 1997). Likewise, 4.5-year-old children who performed well on a behavioural task of inhibition (day-night Stroop task) displayed greater frontal EEG alpha power at rest compared to children who did not do well (Wolfe & Bell, 2004). Another study assessed the developmental change in children's resting-state EEG activity from 10 months old to 4 years, to test whether initial levels of frontal alpha power were related to children's inhibitory control at age 4 (Whedon, Perry, & Bell, 2020). The authors found that, on average, the resting frontal alpha values increased from 10 months to 3 years, and the most significant amount of change was observed by age 2. Moreover, greater increases in frontal alpha power from infancy to preschool were associated with better inhibitory control in preschool. The authors found that children who displayed greater frontal power from 10 months to 4 years old reflected greater prefrontal cortex maturation and thus, greater inhibitory control at 4 years (Whedon et al., 2020).

Other studies have also demonstrated that baseline EEG measures can predict EF in early childhood (Wolfe & Bell, 2007; Kraybell & Bell, 2013). For instance, EEG measured at age 4 is related to EF measured at age 6 (Cuevas, Hubble, & Bell, 2012). Similarly, a study conducted by Kraybill and Bell (2013) found that both parenting behaviour and brain development during infancy together predicted later EF abilities. The authors recorded baseline frontal alpha EEG power of fifty-six 10-month-old infants for 60s while the infant sat in their mother's lap. During the recording, a research assistant manipulated a coloured ball toy to occupy the infant's attention and yield minimal eye movements. When the infants were 4 years old, they returned and their EF was assessed through various cognitive tasks. The particular EF skills of interest included both inhibitory control and working memory. The pattern of EEG findings reported in this article is quite interesting; typically, higher power values are correlated with better EF performance, however, Kraybill and Bell (2013) found that there was a negative correlation between infant frontal alpha power during 10-month baseline recordings and EF abilities at ages 4 and 6 years old. In other words, higher levels of EF performance during childhood were associated with lower frontal alpha EEG power values in infancy. Therefore, the timing of alpha power measurement may be relevant when considering its relationship with later EF abilities.

Socioeconomic Status and Executive Function

Socioeconomic status (SES) is the position of an individual or group within the socioeconomic scale; the position is determined by several contributing factors, such as income, education, occupation, place of residence, and/or parts of society (ethnic origin or religious background). Evidence suggests that SES plays a role in one's early language experience and shapes neural systems that support the development of increasingly complex language and cognitive abilities, including EF. Low SES has been associated with reduced performance on tasks assessing both language and executive function abilities (Bradley & Corwyn, 2002; Clearfield &Niman, 2012). Furthermore, children from lower SES backgrounds have been found to perform poorly on executive function-related tasks of inhibitory control, working memory, executive attention, and flexibility (Hackman et al., 2015). A longitudinal study examining the development of 32 infants at 6-12 months of age from low and high-SES backgrounds revealed that infants experiencing low-SES showed a delayed developmental trajectory compared to high-SES infants on a reaching task requiring cognitive flexibility (Clearfield & Niman, 2012). Consequently, infants from low SES backgrounds exhibit differences in cognitive and EF development, including resting EEG activity (Maguire, & Schneider, 2019). One study compared the resting state EEG of forty-five 8–15-year-olds from low-income homes to children from higher-income homes on a battery of language and cognitive assessments (Maguire, & Schneider, 2019). The authors found that children from low-income homes differed in resting state EEG, such that they displayed lower alpha power than their peers from higher-SES homes. In addition, children experiencing low-SES performed worse on language tasks than high-SES children. To further investigate the relationship between language and EEG, the author performed multiple regression analyses. The analyses revealed an interaction between alpha power and vocabulary, such that children from low-income homes had greater vocabulary scores when their resting alpha power was higher (Maguire, & Schneider, 2019). Jensen and colleagues (2021) found something similar when studying 106 infants aged 6 months old and 187 36-

month-olds, living in Dhaka, Bangladesh. For the SES component, the authors took into account household wealth, assets, and housing materials, as well as psychosocial factors, like maternal perceived stress. For EEG power, the authors examined three different brain regions: frontal, central, and parietal and four frequency bands (theta, alpha, beta, and gamma). The authors found no association between SES and EEG power for 6-month-olds, however, for 36-month-olds, household wealth was negatively associated with absolute power in the beta and gamma bands. Overall, findings suggest that an infant's SES is associated with the development of EEG oscillations (Jensen et al., 2021). Structural differences between children from low- compared to high-SES backgrounds have also been observed in brain areas underlying memory, emotion, and executive control (Brito & Noble, 2014; Lange et al., 2010; Noble et al., 2012).

In contrast, there is a body of evidence that being raised in a bilingual environment confers an advantage to the development of EF (Bialystok, 2011). Some evidence even suggests that being raised in a bilingual context might act as a protective factor against EF difficulties that have been observed in children from low-SES backgrounds. For instance, a study conducted by Hardy and colleagues (2021) examined whether bilingualism moderated associations between attention problems and visual processing and found that bilingual children aged between 6 and 17 years old had greater visual processing advantages than monolinguals when attention problems were high. In other words, if children had been diagnosed with attention problems that typically influence visual attention abilities, these abilities were protected to some degree if children were also bilingual (Hardy et al., 2021). Similarly, Brito and colleagues (2020) tested 18-month-old infants and found that bilingual infants from both low and high-SES backgrounds outperformed monolinguals on a working memory task. Further, bilingual infants were able to recall target actions following a 30-minute delay when stimuli were perceptually different from the demonstration to test stimuli, though no differences in working memory were observed between these bilingual and monolingual groups (Brito et al., 2020). All in all, the relationship between SES and neurophysiological underpinnings of EF in a bilingual context is not well understood.

Executive Function Development in Bilingual compared to Monolingual Language Learners

In the early years, there were a number of misconceptions about the effects of bilingualism, and whether or not children would become confused by exposure to more than one language and thus result in poor language learning (Byers-Heinlein & Lew-Williams, 2013). Young bilingual children are often observed mixing words between two languages in the same sentence, also known as code-mixing (Pearson, 2008). Sometimes code-mixing can be perceived as counterproductive, however, it is a crucial aspect of bilingual development and necessary when learning more than one language simultaneously (Byers-Heinlein & Lew-Williams, 2013). A body of research has suggested that knowing and using more than one language may help with inhibiting irrelevant responses whilst promoting relevant ones, and all in all, conjuring a brain with better cognitive and executive control, which has been coined as the term the 'bilingual advantage'. However, despite the prevalent research on bilingualism, there continues to be a debate whether or not a bilingual advantage exists.

While results supporting a bilingual advantage are mixed, the strongest evidence stems from studies that have examined the performance of infants/young children and older adults (Gunnerud et al., 2020; Lehtonen, 2018). Gunnerud and colleagues (2018) conducted a meta-analytic review comparing bilingual and monolingual children, 18 years of age and under, on different executive function domains. The authors compared 143 studies, with 583 effect sizes, and found the bilingual advantage to be overall significant in EF ($g = 0.06$). Critically, moderation analysis showed that the bilingual group significantly differed from the monolinguals in EF for studies from middle-class socioeconomic backgrounds. The EF skills included inhibition, switching, and monitoring, though the only skill that was safe from publication bias was switching (Gunnerud et al., 2020). Notably, participants from low-SES backgrounds were rarely included in these studies.

Furthermore, the bilingual advantage has been observed through various cognitive and EF-related studies that involve cognitive control and inhibition, as early as infancy and childhood (Bialystok, 2010; Kovács & Mehler, 2009). For instance, at 7 months old, infants that were raised with two languages from birth displayed better cognitive control abilities in an eye-tracking study compared to monolinguals (Kovács & Mehler, 2009). The study consisted of a task whereby infants learned to respond to a speech or visual cue to anticipate a reward on one side of the screen. Results showed that bilingual infants were quicker in redirecting their anticipatory looks when the cue began signalling the reward on the opposite side. Kovács and Mehler (2009) suggested their findings showed bilingual infants having a cognitive control system in place well before the onset of speech that enabled them to process representations more efficiently. Another example is that six-year-old bilingual children have been shown to outperform their monolingual peers on a global-local task used as a test of inhibition (Bialystok, 2010). The task consists typically of congruent and incongruent perceptual displays that are visually presented, and participants respond by inhibiting attention to the salient aspects of the displays (Navon, 1977; Bialystok, 2010). Results revealed that bilingual children produced faster reaction times when inhibiting the competing response compared to monolinguals (Bialystok, 2010). Another study examined 24-month-olds on a Shape Stroop task and similarly found that bilinguals had faster reaction times, significantly outperforming monolinguals (Poulin-Dubois et al., 2011). These results are consistent with previous research on older children that have identified inhibition as an executive function ability that differs most robustly between bilingual and monolingual speakers (Poulin-Dubois et al., 2011). Put another way, executive function tasks that test inhibition (as opposed to other types of EF abilities) may be particularly likely to demonstrate a bilingual advantage. This may be due, in part, to the considerable experience bilingual speakers have switching between languages, which requires some degree of inhibiting words from the language not in use (Bialystok, 2010). Notably, even before children begin to produce language themselves they may engage in this type of inhibition, or selective attention. For example, infants in the early stages of language learning are more likely to accept multiple names for an object if they are raised in a bilingual context, as opposed to a monolingual one. Moreover, evidence suggests that infants exposed to a bilingual environment may engage in attention-switching more frequently than infants raised in a monolingual environment (D'Souza et al., 2020). Consequently, these processes may drive early differences in inhibition abilities between bilingual and monolingual learners.

It should be noted that not all studies find support for a bilingual advantage. For instance, a study conducted by Kalashnikova, Pejovic, & Carreiras (2020) found that the performance of 7-month-old bilingual infants on a task measuring attentional control was no different than same-age monolinguals. The study used an anticipatory-looking paradigm where eye-tracking was used to record infants' gaze patterns. The first exposure was the learning phase (pre-switching) in which an auditory or visual stimulus was presented, followed by the appearance of a puppet on one side of the screen. After nine trials, the test phase was presented in which the location of the puppet was switched to the opposite side. Infants eventually learned to predict that the puppet would appear on one side of the screen after the cue in the pre-switch phase. The post-switching phase imposed greater demands on the infants, such that they needed to rely on their attention and cognitive control skills to abandon the previously learned response pattern and successfully learn the new location of the puppet. Correct responses were based on the number of anticipatory looks to the wrong location. The authors claim that bilingual infants did not show any significant advantages in attention, however, patterns of attentional allocation did differ between monolingual and bilingual infants. Similarly, a study conducted by Poulin-Dubois and colleagues (2022) with 17-month-old infants also did not find evidence of a bilingual advantage using a cognitive flexibility task. The study used a detour reaching task which assessed conflict resolution and a delayed response task to assess shifting and cognitive flexibility. While these studies did not find an advantage in performance for bilingual compared to monolingual language learners, they nonetheless found that bilingually exposed infants displayed different attentional patterns than monolingually exposed infants; specifically, bilingual infants were found to be faster at detecting and directing their attention to new auditory or visual information than monolingual infants. Authors suggest that bilingual infants' experience of encountering language switches in their day-to-day communicative interactions requires them to selectively attend to and track details that are relevant for encoding meaningful linguistic information in each language, which may lead them to be faster to attend to novel information. This view has received further support from neurophysiological studies showing that unlike monolinguals, bilingually exposed infants engage attentional neural networks in a variety of language processing tasks (Arredondo, Hu, Stterfield, & Kovelman, 2017; Ferjan Ramírez, et al., 2017; Petitto et al., 2012). This experience of selectively allocating attention to changing or novel cues in the linguistic environment may lead bilingual and monolingual infants to differ in their attention towards novelty. It may also contribute to the development of a capacity referred to as executive attention, which has been proposed as a domain in which experience-driven effects of the bilingual environment may be most likely to emerge (Bialystok, 2017).

Further, studies suggest that features of the bilingual environment may contribute to variation in neural development, and in early attention patterns that might be predictive of later EF (Arredondo, Aslin, & Werker, 2022; Arredondo et al., 2022). Arredondo and colleagues (2022) examined this phenomenon using one hundred and fifty-two 6 to 10-month-old monolingual and bilingual infants, all of whom underwent a cueing attentional orienting task. The task consisted of infants being oriented to a cue before an object appeared either on the same side or the opposite side of the display. The results showed that bilingual infants had significantly faster latencies than the monolinguals during the incongruent trials when the conditions were most cognitively demanding (Arredondo et al., 2022). Consequently, from the pattern of results, the authors inferred that the bilingual experience facilitates attention-shifting and orienting behaviour. This attention-switching behaviour can also be observed in another study that also employed a cueing attentional orienting task, testing 6 to 10-month-old monolingual and bilingual infants (Arredondo et al., 2022). The study also measured brain activity using functional near-infrared spectroscopy. Task performance did not differ between monolinguals and bilinguals, however, neural activity did. At 6 months of age, both groups showed greater activity for valid (cue on the same side as object) trials than invalid trials (incongruent- cue on the opposite side) in frontal regions, however, the left hemisphere was more activated for bilinguals, whereas the right hemisphere was more activated for monolinguals. When infants were 10 months old, bilinguals had greater activity for invalid trials in the bilateral frontal regions, whereas monolinguals showed greater activity for the valid trials in the left frontal regions. The authors concluded that these different early patterns of neural activity suggest that early dual language exposure might affect cortical organization supporting non-linguistic EF during the first year of life (Arredondo et al., 2022). Note, unlike much of EF research that has been conducted during childhood and adolescence, this study examines infants during the first year of life. Studying infants' EF during the first year of life is advantageous because there still remains a lot unknown about the precursors of EF. Thus, studying EF at such an early age can provide insight on when these precursors become present.

Current Study

There is little research exploring associations between SES and early neural predictors of EF, and even less exploring the interaction between SES and bilingualism. Thus, in the current study I aim to test the association between SES and early neural predictors of EF, as well as the interaction between SES and bilingualism. This research is aligned with prior work that has found associations between SES and early neurodevelopment, as well as better performance and different neural activity between bilingual and monolingual speakers, from infancy and early childhood. As aforementioned, it is important to study infants during the first year of life because there is still a lot of unknown about the precursors for EF. Being able to study young infants can provide insight into when these precursors emerge. There is also limited research that tests for EF differences between bilingual and monolingual children from low-SES backgrounds. Given the relationship observed between frontal alpha power during infancy and EF abilities during early childhood (Kraybill & Bell, 2012; Perone & Gartstein, 2019) my neural measure of EF will be frontal alpha power in infancy (i.e., 2-12 months), recorded during 5 minutes of baseline EEG. Infants tested are part of a longitudinal study exploring associations between early life adversity and neurodevelopmental outcomes.

The aims of the current proposal are to address the following research questions: a) does SES predict EEG frontal alpha power during infancy? b) does frontal alpha power during infancy differ between monolingual and bilingual exposed infants?; And, c) does language status moderate associations between SES and frontal alpha power? More specifically, can bilingualism be viewed as a protective factor in EF development within a low-SES context? The findings of this project will inform whether associations between SES and very early neurodevelopment (i.e., during infancy) vary as a function of language exposure and whether being bilingual can account for some of the individual differences in EF abilities for children from low-SES backgrounds.

Methods

Participants

Data come from a cohort study that took place at Boston Children's Hospital/Harvard Medical School and Children's Hospital of Los Angeles, examining responses to early adversity. Enrollment occurred when infants were approximately 2 months of age. Mother-infant dyads (*n* = 116) were followed up longitudinally at 2, 6, 9, 12, and 24, and 36 months of age. Participants were recruited from Boston Children's Hospital Primary Care Center, Boston, Massachusetts, and AltaMed Clinic, Children's Hospital Los Angeles, Los Angeles, California, from January 1, 2016, to March 1, 2018. These clinics predominantly serve families from low-income backgrounds (i.e., those below the federal poverty level, who qualify for public health insurance). Exclusion criteria were gestational age younger than 37 weeks; birth weight less than 2500 g; identified genetic, metabolic, or neurologic disorders; uncorrected vision difficulties; or birth-related complications (e.g., extended stay in the neonatal intensive care unit). Parents provided written informed consent. The Boston Children's Hospital Institutional Review Board and the Children's Hospital Los Angeles Institutional Review Board approved all procedures.

Background and Demographic Information

Standard demographic information was collected from families using questionnaires, including child age, child sex, child weight at birth, maternal age, maternal education, family income, and race/ethnicity. Because not all participants reported family income, zip code data were used to determine the percentage of households below the federal poverty level within each participant’s neighbourhood (American Community Survey 5-Year Data 2015 US Census tract); these neighbourhood level data were used as an additional socioeconomic marker.

Language Context

As part of the demographic information collection, participants (participants’ mothers) were asked one question about language(s) spoken at home: whether they spoke English, Spanish, both, or other. For the purposes of the present study, an infant was defined as a bilingual language learner if their caregiver endorsed “both” (i.e., both Spanish and English were present in the home) or if they selected “other” and listed two languages. An infant was defined as a monolingual language learner if their caregiver endorsed solely “English” or “Spanish” or if they selected “other” and only listed one language.

Baseline EEG

Identical protocols were used at each collection site. Infant recordings were completed using a 128-Channel Hydrocel Sensor Net System (EGI Inc) soaked in a 37°C salt water solution. Recordings were conducted in dimly lit rooms with low electrical-signal backgrounds. Infants were 60 cm from a computer monitor (Dell model P2314Ht, 49 × 29 cm) held backward over their mother’s shoulder or seated and facing forward on her lap. NetAmps 300 Amplifier and NetStation, version 4.5.4 (Boston Children's Hospital) and NetAmps 400 Amplifier and NetStation, version 5 (Children's Hospital Los Angeles) were used to record EEG data. Data were amplified and sampled at 500 Hz while infants watched a video of infant toys for up to 5 minutes (mean impedance, <100 kΩ). A trained researcher engaged minimally with infants using a toy and bubbles to redirect attention toward the screen only when necessary. Electroencephalographic data were collected from 112 infants at the age of 2 months old. After processing and data quality checks, EEG recordings from 110 participants were deemed suitable for analysis. At 6 months, data were collected from 99 infants, and after data quality checks, EEG recordings from 98 participants were suitable for analysis. At 9 months, data were collected from 92 infants, and after data quality checks, EEG recordings from 90 participants were suitable for analysis. At 12 months, data were collected from 88 infants, and after data quality checks, EEG recordings from 87 participants were suitable for analysis. Data inclusion criteria are described in the next section.

EEG Analysis

Raw EEG files were exported from NetStation, version 4.5.4 in MATLAB format (MathWorks Inc) and preprocessed using the Harvard Automated Processing Pipeline for Electroencephalography (Gabard-Durnam et al., 2018), optimized for use with infant EEG and used with MATLAB, version 2014b and EEGLAB, version 14.0.0b. The Batch EEG Automated Processing Platform was used for subsequent spectral analysis (Levin et al., 2018). Within the Harvard Automated Processing Pipeline for Electroencephalography, data were band-pass filtered at 1 to 249 Hz. A subset of 46 channels was selected for further processing, including standard 10-20 electrodes and additional electrodes based on previous infant reports. Independent component analysis and advanced processing techniques were used to correct artifacts, and 2-second segments were extracted. Segments with remaining artifacts were removed before re-referencing to the average. Power spectra for each channel were extracted using a fast Fourier transform with a multitaper window. For each participant, mean power across all segments was calculated. Log10-transformed absolute power was calculated for several frequency bands of interest: delta (2-4 Hz), theta (4-6 Hz), low alpha (6-9 Hz), high alpha (9-13 Hz), beta (13-30 Hz), and gamma (30-50 Hz). Low alpha power (6-9 Hz) was used for all analyses in this study, as this range is typically used to define alpha power during the infancy period. Consistent with the literature, power in the alpha band was averaged across left and right frontal electrodes (F3, F4, F7, F8) to obtain a measure of absolute frontal alpha power. Relative power was calculated as power in the alpha frequency band divided by total power. The present study reports both absolute and relative EEG power, as is common in developmental research.

Statistical Analysis

All statistical data analyses were performed using SPSS version 29.0 (IBM Inc). Aim 1 tested whether there are associations between SES and frontal alpha power at any time point (2, 6, 9, or 12 months). Initial bivariate Pearson correlations were run to explore associations between all variables of interest. Hierarchical linear regressions were used to test relationships between SES variables and an early neural predictor of EF (EEG 6-9 Hz alpha power) adjusting for control variables of interest (infant age). Child age was entered in Step 1 of the model and maternal education and neighbourhood income were entered in Step 2. Note, models included child age as a control variable because considerable change in EEG power is observed across the first year. It is hypothesized that lower SES (i.e., higher rates of neighbourhood poverty or lower levels of maternal education) will be associated with lower alpha power. Aim 2 tested whether frontal alpha power during infancy differs between monolingual and bilingual exposed infants.

Bonferroni-corrected independent samples t-tests were used to compare EEG 6-9 Hz alpha power between bilingual and monolingual groups at each time point. Comparisons were conducted for both absolute and relative alpha power. Because there was an unequal sample size between the bilingual and monolingual groups, I confirmed equality of variances across groups by checking Levene's test for equality of variances. If equal variance was assumed I proceeded with a standard t-test, and if equal variance could not be assumed, I reported Welch's t-test outcomes. Greater EEG frontal alpha power in the bilingual compared to the monolingual group would support the hypothesis that a bilingual advantage is observed within a predominantly low-SES context. Aim 3 tested whether language status moderates associations between SES and frontal alpha power. Moderation analyses were performed using the PROCESS toolbox in SPSS (Hayes, 2012). Moderation analysis was conducted as a follow-up for regression models that determined a significant association between SES variables and frontal alpha power. SES variables, language group (bilingual vs monolingual) and the interaction between these variables (moderation term) served as the predictors and frontal alpha power was the outcome variable. A significant association between the interaction term and frontal alpha power would support the hypothesis that associations between SES and frontal alpha power differ as a function of language group.

Results

Demographics

Standard demographic information was collected from families upon study enrollment and at subsequent study visits (see Table 1). Group comparisons between monolinguals and bilinguals were conducted. Groups significantly differed on only three variables: neighbourhood poverty (p = .010), maternal age (p = 0.012) and child age at 12 months (p= 0.039). Regarding languages spoken at home, participants stated they spoke English (*n*= 59), Spanish (*n*= 32), and both English and Spanish (*n*= 13). Other languages included: Korean (1), both Norwegian and German (1), Somali (1), Cape Verde Creole (2), both Russian and Swedish (1), Haitian Creole (1), both English and Portuguese Creole (1), and Turkish (1). Thus, 98 families reported use of one language in the home, and 17 reported using two languages.

Table 1

Demographic information was collected from mother-infant dyads at the time of the recording session for monolinguals and bilinguals

	Monolinguals		Bilinguals		*p*
	No. (%)	Mean (Range; SD)	No. (%)	Mean (Range; SD)	
Child gender					.660
Male	52 (53.1)		10 (58.8)		
Female	46 (46.9)		7 (41.2)		
Maternal education					.053
8th grade	6 (6.1)		0		
<High school	16 (16.3)		1(5.9)		
High school/GED	45 (45.9)		9 (52.9)		
Associate's degree	15 (15.3)		2 (11.8)		
Bachelor's degree	7 (7.1)		3 (7.6)		
Master's degree	6 (6.1)		1 (5.9)		
MD, JD, PhD	0		1 (5.9)		
Did not disclose	3 (2.6)		0		
Maternal age	98	29.16 (24; 3.72)	17	26.29 (15; 3.72)	.012
Child age					
2m	98	2.37 (1.48; 0.33)	17	2.50 (1.12; 0.34)	.139
6m	84	6.20 (2.24; 0.46)	16	6.13 (1.87; 0.58)	.597
9m	80	9.27 (2.30; 0.46)	14	9.24 (1.61; 0.49)	.824
12m	82	12.30 (3.0; 0.63)	13	11.90 (2.16; 0.63)	.039
Family income					.805
< $5000	11 (11.2)		3 (17.6)		
$5000-11,999	7 (7.1)		2 (11.8)		
12,000-15,999	8 (8.2)		2 (11.8)		
16,000-24,999	9 (9.2)		0		
25,000-34,999	12 (12.2)		2 (11.8)		
35,000-49,999	9 (9.2)		1 (5.9)		
50,000-74,999	4 (4.1)		2 (11.8)		

75,000 - 99,999	5 (5.1)		2 (11.8)		
100,000 or greater	4 (4.1)		0		
Did not know	20 (20.4)		2 (11.8)		
Did not disclose	9 (9.2)		1 (5.9)		
% Neighbourhood poverty (from census)	93	0.23 (0.46; 0.10)	16	0.30 (0.2; 0.08)	.010
Race					.236
White	45 (45.9)		11 (64.7)		
Black/African American	35 (35.7)		1 (5.9)		
Chinese	1 (1.0)		0		
Filipino	1 (1.0)		0		
Korean	1 (1.0)		0		
Vietnamese	1 (1.0)		0		
Biracial/Multiracial	9 (9.2)		2 (11.8)		
Did not disclose	5 (5.1)		3 (17.6)		
Ethnicity					.160
Not Hispanic, Latino, or Spanish origin	44 (44.9)		3 (17.6)		
Mexican/Mexican American	15 (15.3)		6 (35.3)		
Puerto Rican	8 (8.2)		1 (5.9)		
Cuban	1 (1.0)		0		
Hispanic, Latino, or Spanish origin	30 (30.6)		7 (41.2)		
Did not disclose	0		0		

Bivariate Correlations

Pearson correlations were performed to explore associations between all variables of interest at the 2, 6, 9, and 12-month time points, and are presented for descriptive purposes (see Tables 3a-d). As expected, positive correlations were observed amongst socioeconomic variables at each time point (e.g., family income, neighbourhood poverty, maternal education). Associations between socioeconomic variables and alpha power were also observed at all time points. Notably, age was positively associated with alpha power within each time point. Therefore, age was included as a covariate in all regression models with alpha power as the outcome variable.

Table 2a

Bivariate correlations between variables of interest at the 2 month timepoint.

	1	2	3	4	5	6	7
1. Maternal Education	-						
2. Neighbourhood Poverty	-.286**	-					
3. Child Age (2 months)	-.122	.252*	-				
4. Child Sex	.057	-.129	016	-			
5. Family Income	.568**	-.477**	-.137	-.010	-		
6. Absolute Frontal Alpha Power	.152	-.032	.256**	.050	-.032	-	
7. Relative Frontal Alpha Power	-.119	.047	-.063	.020	.051	.059	-

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Table 2b

Bivariate correlations between variables of interest at the 6 month timepoint.

	1	2	3	4	5	6	7
1. Maternal Education	-						
2. Neighbourhood Poverty	-.189	-					
3. Child Age (6 months)	.147	.004	-				
4. Child Sex	.052	-.059	-.025	-			
5. Family Income	.522**	-.435**	.198	.017	-		
6. Absolute Frontal Alpha Power	.122	-.234*	.308**	.070	.236	-	
7. Relative Frontal Alpha Power	-.112	-.167	.174	-.088	.067	.565**	-

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Table 2c

Bivariate correlations between variables of interest at the 9 month timepoint.

	1	2	3	4	5	6	7
1. Maternal Education	-						
2. Neighbourhood Poverty	-.197	-					
3. Child Age (9 months)	.078	-.062	-				
4. Child Sex	.141	-.066	-.052	-			
5. Family Income	.501**	-.406**	.191	.020	-		
6. Absolute Frontal Alpha Power	.224*	-.266*	.076	.169	.033	-	
7. Relative Frontal Alpha Power	.168	-.305**	.190	.130	-.022	.557**	-

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Table 2d

Bivariate correlations between variables of interest at the 12 month timepoint

	1	2	3	4	5	6	7
1. Maternal Education	-						
2. Neighbourhood Poverty	-.208	-					
3. Child Age (12 months)	.234*	-.193	-				
4. Child Sex	.043	-.105	.101	-			
5. Family Income	.514**	-.384**	.469**	.001	-		
6. Absolute Frontal Alpha Power	.064	-.193	.125	-.048	.038	-	
7. Relative Frontal Alpha Power	.021	-.293**	.218	.008	.160	.569**	-

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

Associations Between SES and Frontal Alpha Power

Hierarchical linear regressions were used to test whether SES variables: maternal education and neighbourhood poverty were associated with frontal alpha power (Aim 1). Family income was not included due to the high amount of missing data on this variable. Child age at the time of EEG recording was entered in Step 1 of the model, because of observed correlations between age and alpha power at each time point. SES variables (maternal education and neighbourhood income) were entered in Step 2. Separate regression models were run for each time point (2, 6, 9, 12 months), and with absolute and relative frontal alpha power as the outcome measures, respectively.

When infants were 2 months old, step 1 of the model predicting absolute frontal alpha power was significant ($R^2 = .07$, $F(1, 92) = 6.77$, $p = .011$) and child age was significantly and positively associated with frontal alpha power. The inclusion of SES variables in step 2 did not explain additional variance. For relative alpha power, neither of the variables from steps 1 nor 2 of the model predicted frontal alpha power (see Table 3a).

At 6 months, step 1 of the model predicting absolute frontal alpha power was significant ($R^2 = .10$, $F(1, 79) = 8.82$, $p = .004$). The inclusion of maternal education and neighbourhood income in Step 2 did not explain additional variance (see Table 3b). For relative alpha power, neither of the variables from steps 1 and 2 of the model predicted frontal alpha power.

At 9 months, step 1 of the model predicting absolute or relative frontal alpha power was not significant. The inclusion of maternal education and neighbourhood poverty in Step 2 did explain significantly additional variance ($R^2 = .131$). Within this model, maternal education significantly predicted absolute frontal alpha power ($p = .028$), but neighbourhood poverty did not. For relative frontal alpha power, Step 2 also explained additional variance. Here, neighbourhood poverty significantly predicted relative alpha frontal power (p = .015), however maternal education did not (see Table 3c).

At 12 months, step 1 of the model, child age, did not explain a significant amount of variance in absolute frontal alpha power. However, child age did account for a significant amount of variance in relative frontal alpha power (R^2 = .062, F(1, 72) =7.76, p = .032) and was positively associated with frontal alpha power (B = 0.12 and p = .032). Within Step 2, neither maternal education nor neighbourhood poverty predicted frontal alpha power. However, for relative frontal alpha power, neighbourhood poverty was a significant negative predictor (p = .01). Maternal education did not significantly predict relative frontal alpha power (see Table 2d).

Regression models demonstrated that SES variables were associated with frontal alpha power by 9 and 12 months of age. Associations appeared most consistent between neighbourhood poverty and relative frontal alpha power, such that higher rates of neighbourhood poverty predicted lower relative alpha power at these time points.

Table 3a

Linear regressions examining associations between frontal alpha power (absolute and relative) and SES variables (maternal education and neighbourhood poverty) at 2 months.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Step 1		
Child Age	-.167 [.040,.295] .011*	-.004 [-.016,.008] .503
Model Statistics	R^2 = .069 Adj R^2 = .058	R^2 = .005 Adj R^2 = -.006
Step 2		
Child Age	.192 [.061, .322] .004*	-.006 [-.019, .007] .370
Maternal Education	.036 [-.002,-.074] .060	-.002 [-.006,.002] .243
Neighbourhood Poverty	-.099 [-.541,.343] .657	.008 [-.035,.051] .724
Model Statistics	R^2 = .114*	R^2 = .025

*$p < .05$

Table 3b

Linear regressions examining associations between frontal alpha power (absolute and relative) and SES variables (maternal education and neighbourhood poverty) at 6 months.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Step 1		
Child Age	.144 [.048,.241] .004*	.133 [-.003,.019] .008*
Model Statistics	R^2 = .100 Adj R^2 = .089*	R^2 = .028 Adj R^2 = .016
Step 2		
Child Age	.143 [.048, .239] .004*	.010 [-.001, 020} .076
Maternal Education	.003 [-.038,.045] .871	-.004 [-.008,.001] .087
Neighbourhood Poverty	-.491 [-.940,-.041] .033*	-.047 [-.097,.002] .062
Model Statistics	R^2 = .156*	R^2 = .093

*p < .05

Table 2c

Linear regressions examining associations between frontal alpha power (absolute and relative) and SES variables (maternal education and neighbourhood poverty) at 9 months.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Step 1		
Child Age	.037 [-.074,.148] .508	.011 [-.002,.024] .102
Model Statistics	R^2 = .006 Adj R^2 = -.007	R^2 = .034 Adj R^2 = .021
Step 2		
Child Age	.018 [-.088, 123] .741	.009 [-.003, 021] .156
Maternal Education	.048 [.005,.091] .028*	.003 [-.002,.008] .261
Neighbourhood Poverty	-.494 [-.994.006] .053	-.073 [-.132,-.014] .015*
Model Statistics	R^2 = .131*	R^2 = .134*

**p* < .05

Table 3d

Linear regressions examining associations between frontal alpha power (absolute and relative) and SES variables (maternal education and neighbourhood poverty) at 12 months.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Step 1		
Child Age	.031 [-.040,.102] .392	.012 [.001,.023] .032*
Model Statistics	R^2 = .010 Adj R^2 = -.004	R^2 = .062 Adj R^2 = .049*
Step 2		
Child Age	.019 [-.055, 092] .613	.010 [-.001, .021] .077
Maternal Education	.000 [-.043,.042] .996	-.002 [-.008,.004] .552
Neighbourhood Poverty	-.485 [-.850.081] .104	-.087 [-.156,-.018] .014*
Model Statistics	R^2 = .048	R^2 = .141*

**p* < .05

Comparison of Alpha Power Between Bilinguals and Monolinguals

Independent samples t-tests were run to test whether absolute or relative frontal low alpha power differed between monolingual and bilingual infants at each time point (2, 6, 9, and 12 months: Aim 2). Bilingual infants had higher absolute alpha power at 2 months of age ($t(100) = -2.10$, $p = 0.039$). Monolinguals had higher relative alpha power at 6 months of age ($t(85) = 2.19$, $p = 0.032$), though these did not survive correction for multiple comparisons. No significant differences were observed at other time points (see Table 4).

Table 4

Independent Samples t-tests Comparing Frontal alpha power between Bilingual and Monolingual Infants.

	df	*t* value	*p*-value	Monolingual mean alpha power (SD)	Bilingual mean alpha power (SD)
2-months					
absolute	100	-2.097	0.039*	-.5206 (.1843)	-.4003 (.3218)
relative	100	-0.453	0.651	.1428 (.0204)	.1453 (.0159)
6-months					
absolute	85	1.039	0.302	-.1985 (.0237)	-.2641 (.2438)
relative	85	2.185	0.032*	.1496 (.0223)	.1353 (.0184)
9-months					
absolute	83	1.009	0.316	-.0601 (.2155)	-.1288 (.2788)
relative	83	-0.157	0.875	.1572 (.0266)	.1585 (.0280)
12-months					
absolute	82	-0.529	0.598	.0218 (1769)	.0549 (.2484)
relative	82	-1.180	0.241	.1668 (.0294)	.1786 (.0321)

$^*p < .05$.

Bilingualism Moderates Associations Between SES and Frontal Alpha Power

Where significant associations between SES variables and alpha power were observed (neighbourhood poverty and frontal alpha power (absolute and relative) at 9 and 12 months old), moderation analyses were used to test whether language group (bilingual vs monolingual) moderated observed associations between SES and alpha power. At 9 months, an overall model including language group, neighbourhood poverty, and the interaction between the two, explained a significant amount of variance in relative frontal alpha power (p = .0026). Within this model, the interaction between neighbourhood poverty and relative frontal alpha positively and significantly predicted relative frontal alpha power (B= .2452, p= .0256). Neighbourhood poverty also remained a significant predictor (B= -.0775, p= .0128) (see Table 5a). Analysis of conditional effects demonstrated a significant negative association between neighbourhood poverty and relative frontal alpha power for the monolingual group (b = -.150, SE = 0.31, p = 0.0004), but no significant association for the bilingual group (b = .850, SE = 0.10, p = .2086). Figure 1 plots associations between neighbourhood poverty and frontal alpha power for monolingual and bilingual groups at 9 months. Neighbourhood poverty is shown at +/- 1 SD from the mean, as is standard for these types of visualizations.

At 12 months, an overall model including language group, neighbourhood poverty, and the interaction between the two, explained a significant amount of variance in relative frontal alpha power (p = .0103). However, neither the interaction nor language group was a significant predictor. Neighbourhood poverty remained a significant predictor of relative frontal alpha power (B= -.0979, p= .0050) (see Table 5b). Given that the interaction term was non-significant, no moderation effect was observed at 12 months. Figure 2 plots associations between neighbourhood poverty and frontal alpha power for monolingual and bilingual groups at 12 months. Neighbourhood poverty is shown at +/- 1 SD from the mean, as is standard for these types of visualizations. Note that the pattern observed at 9 months is replicated, though the moderation is not significant.

Figure 1

Language group significantly moderates associations between neighbourhood poverty and relative frontal alpha power at 9 months.

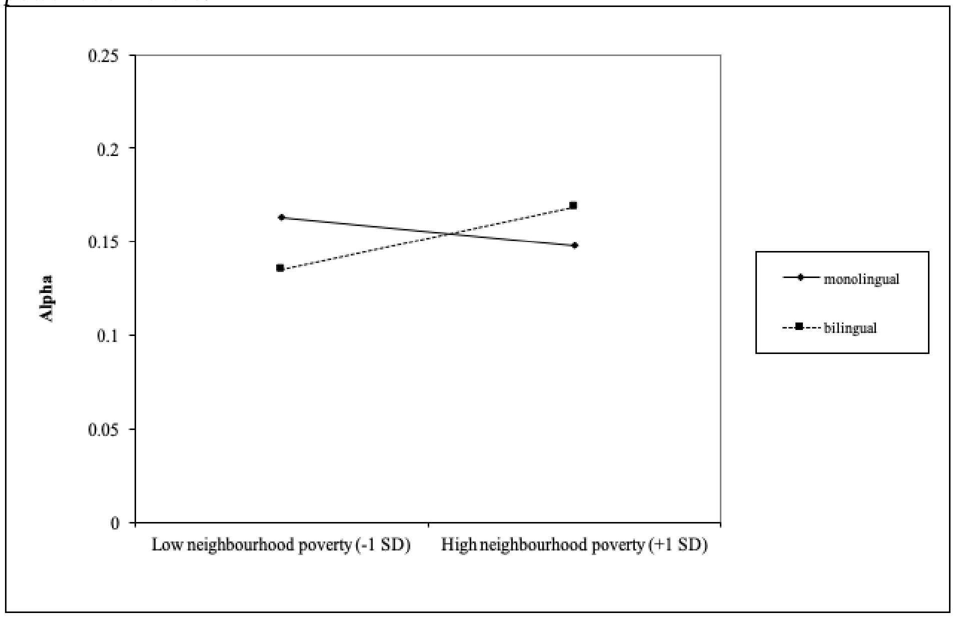

Figure 2

Language group does not significantly moderate associations between neighbourhood poverty and relative frontal alpha power 12 months.

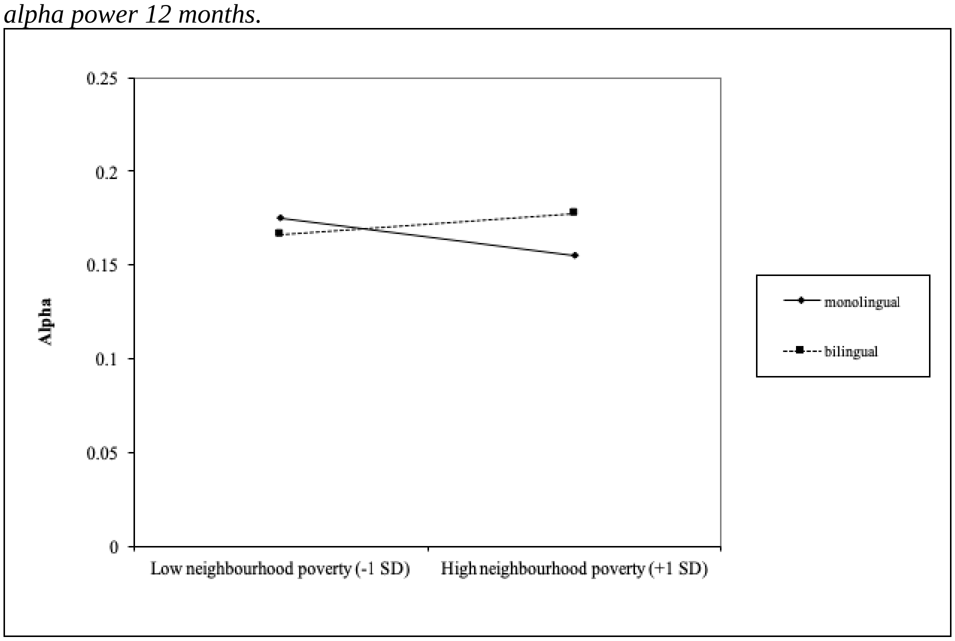

Table 5a.

Moderation analysis testing whether bilingual status moderates associations between neighbourhood poverty and frontal alpha power (absolute and relative) at 9 months old.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Neighbourhood Poverty	-.5865 [-1.1291,-.0439] .0345*	-.0775 [-.1380,-.0170] .0128*
Bilingualism	-.0469 [-.2282,.1344] .6080	-.0040 [-.0242,.0162] .6960
Interaction	.3207 [-1.6029,2.2443] .7408	.2452 [.0307,.4598] .0256*
Model Summary	$R^2 = .0789$ $p = .0985$	$R^2 = .1699$ $p = .0026$*

*$p < .05$

Table 5b

Moderation analysis examining bilingual status moderating associations between neighbourhood poverty and frontal alpha power (absolute and relative) at 12 months old.

	Absolute Frontal Alpha Power	**Relative Frontal Alpha Power**
	B [95% CI] *p*	B [95% CI] *p*
Neighbourhood Poverty	-.3854 [-.8448,.0740] .0988	-.0979 [-.1653,-.0304] .0050*
Bilingualism	.0217 [-.1622,.2056] .8145	.0064 [-.0207,.0334] .6407
Interaction	.3059 [-1.5158,2.1276] .7389	.1535 [-.1141,.4210] .2567
Model Statistics	$R^2 = .0424$ $p = .3578$	$R^2 = .1406$ $p = .0103$*

*$p < .05$

Discussion

In the present study I sought to examine whether SES variables were associated with an early neural predictor of EF -frontal alpha power during infancy. While there were no associations between SES and frontal alpha power during the first half year of life, robust negative associations between SES variables and frontal alpha power were evident by 9 months of age, and these continued through 12 months. Results also suggested that associations between SES and frontal alpha might depend, to some degree, on language learning context. In particular, being raised in a bilingual environment might act as a buffer against potential negative effects of SES on neural correlates underlying EF. However, further studies are needed to validate this exploratory claim.

The first aim of the study was to test whether SES variables were associated with frontal alpha power. Results showed that at 9 months, maternal education positively predicted absolute frontal alpha power and neighbourhood poverty negatively predicted relative frontal alpha power. Further, at 12 months, neighbourhood poverty continued to negatively predict relative frontal alpha power such that rates of neighbourhood poverty negatively predicted frontal alpha power at both 9 and 12 months. Results are consistent with prior evidence suggesting that experiencing low-SES and high stress environments associated with poverty early in life are predictive of features of early neural development, measured using EEG (Brito et al., 2016; Pierce et al., 2019; Tomalski et al., 2013). The neighbourhood poverty metric used in the present study is a highly relevant and underutilized measure, as it may reflect access to support and resources within the broader community. Indeed, neighbourhood disadvantage has previously been linked to both behavioural and neural development (Hackman et al., 2021; Jeon et al., 2014; Leventhal & Brooks-Gunn, 2000; Taylor et al., 2020; publication forthcoming). High levels of poverty in the community may reflect features of the early environment such as reduced access to resources, including quality childcare or early education settings, that may increase levels of stress within the family and impact the caregiving relationship. While individual neighbourhood variables aren't separable in the present study, theoretical models such as the family stress and family investment models (e.g., reviewed in Hackman et al., 2010; 2015) support pathways such as these, which link experiences of poverty to developmental outcomes. At the same time, prior studies that have examined associations between SES and EF have also found that both family income (Lawson et al., 2016) and family income-to-needs (i.e., a calculation of family income relative to the number of family members supported by that income and the poverty threshold) are negatively associated with aspects of EF, including working memory, in young infants aged 54 months, as well as children in grade 1 and 2 (Hackman et al., 2015). Notably, some studies on EF development have found income-level variables to be stronger predictors of developing EF than other indicators of SES, such as maternal education.

Nonetheless, prior studies have also found maternal education to be highly correlated with both income and poverty (e.g., family income often provides the necessary resources for mothers to be able to attain higher levels of education) as well as with children's developmental outcomes (e.g., Pierce et al., 2019). Although the present study observed a positive relationship between maternal education and frontal EEG power at 9 months, this relationship was not observed at 12 months. This may suggest that, in the present study, income variables are more strongly predictive of early predictors of EF than maternal education. Alternatively, many studies have only found associations between maternal education and developmental outcomes (e.g., language) when higher levels of maternal education are included in the sample. That is, there may not be a linear relationship between maternal education and the development of alpha power, but rather a cut-off by which effects begin to emerge. The majority of mothers within our sample (48%) reported high school as the highest level of education attained. Therefore, there may not have been enough mothers at the higher end of the education spectrum for a strong linear relationship to emerge.

The observation that associations between SES and frontal alpha power emerged by 9 months of age, but not earlier, is consistent with prior results that have demonstrated associations between alpha power and EF beginning around this age. For example, Bell and Fox (1997) found that infants who performed well on inhibitory control and working memory tasks also had larger frontal baseline EEG alpha power at 8 months of age than infants who did not perform well on these tasks (Bell & Fox, 1997). There may be something relevant about the development of neural circuitry underlying EF that leads to associations between environmental variables - like SES - and developing EF, to emerge around this age. While some studies have found associations between SES variables and developing EEG from 2-6 months of life (Pierce et al., 2019; Tomalski et al., 2013), others have found no associations until later in development (e.g., Jensen et al., 2021). The link between specific environmental variables and the developing EEG may depend on the specific measures in question. Eight to twelve months might represent an important window for the emergence of early EF abilities.

The second aim of this study was to determine whether bilingual infants displayed higher frontal alpha power than monolingual infants at any time across the first year of life. Results showed an inconsistent pattern that largely contradicted this hypothesis. Namely, while bilingual infants displayed marginally higher alpha power at 2 months (absolute), monolinguals had marginally higher alpha power at 6 months (relative). No significant differences in alpha power emerged at any other time points. Results are not entirely in line with prior data, as previous studies have typically found higher alpha power in bilinguals compared to monolinguals (Bice, Yamasaki, & Prat, 2020; Calvo, Grundy, & Bialystok, 2023). Prior work has predominantly been conducted with adults, however, and it is possible that global differences in alpha power do not emerge until a later point in development. Another possible explanation for the inconsistent pattern observed in the present study is that the bilingual group size was relatively small, which reduces statistical power to detect small differences between groups. Follow up work should include a larger sample of bilingual participants to determine whether this pattern replicates. Another reason differences in alpha power may not be apparent across the language groups is because of confounding differences in demographic variables between monolingual and bilingual groups present in this sample. Notably, the bilingual group experienced significantly higher levels of neighbourhood poverty than the monolingual group. Given that higher neighbourhood poverty predicted lower alpha power, this may have obscured differences in alpha power between language learning groups. Again, a larger sample size would have allowed more effective adjustments for confounding variables when comparing these two groups.

It may also be the case that comparing alpha power between bilingual and monolingual groups during executive function tasks, as opposed to at baseline, might reveal stronger differences between these groups. Nonetheless, examining frontal alpha power during baseline in bilingual versus monolingual infants is highly advantageous because it allows measurement of a very early predictor of EF abilities during a time when it is challenging or impossible for infants to complete complex EF tasks. Determining differences in emerging neural correlates underlying EF during infancy contributes to our ability to identify individuals experiencing challenges with EF, potentially allowing targeted intervention to occur early in development, when neural systems may be most malleable, and prior to the emergence of behavioural challenges. Indeed, as previously reviewed, prior studies support the notion that frontal alpha power in infancy is a good predictor of EF, in particular attention-shifting and cognitive control (Navon, 1977;

Bialystok, 2010; Arredondo et al., 2022). For instance, Whedon, Perry, and Bell (2020) assessed resting frontal alpha from 10 months to 3 years of age and found that initial levels of alpha power were positively correlated to children's inhibitory control performance at age 4. While we did not observe differences between monolingual and bilingual participants' alpha power in the present study, examining frontal alpha power nonetheless contributes to our understanding of the development of EF at its very earliest stages.

The third aim of this study was to test whether language-learning context moderated observed associations between SES and alpha power during infancy. In other words, whether being bilingual was a protective factor against any negative associations observed between SES and frontal alpha. Results showed that at 9 months there was a negative association between SES and alpha only for the monolingual group, such that when neighbourhood poverty was higher alpha power was lower. Based on the literature, this result is as expected, since coming from a low-SES neighbourhood has been associated with challenges to the early development of EF (Bradley & Corwyn, 2002; Clearfield & Niman, 2012). Notably, however, the moderation analysis revealed that there was no association between SES and 9-month frontal alpha power for the bilingual group. That is, associations between SES and alpha power at this time point varied as a function of language learner status, and negative associations between these variables were driven by the monolingual group alone. A similar pattern was observed at 12 months, however the moderation was not significant. This pattern of results is similar to that found by Brito and colleagues (2020), which showed memory advantages for bilingual infants from both low versus high SES backgrounds (Brito et al., 2020). Specifically, Brito and colleagues (2020) found significant differences between the two language groups for tasks that tested memory generalization from 6 to 24 months of age. Bilingual infants outperformed monolingual infants regardless of SES. Hence, the authors suggested that being bilingual may protect against some of the disadvantages that have been associated with experiencing low SES. In addition, Gonzalez (2001) found that Hispanic, bilingual children from low-SES backgrounds performed at higher cognitive developmental levels than middle-high SES monolingual counterparts. Notably, however, in this study SES was found to be a stronger predictor of cognitive development than cultural or linguistic factors for these Hispanic, bilingual children from low-SES contexts, suggesting the importance of considering the underexplored interaction between these factors.

Together, the present study supports limited prior research to provide evidence that learning more than one language may confer some developmental protection for children experiencing low-SES. Future studies should explore this question with a much larger sample of bilingual infants. Future studies should also include additional information about the bilingual experience (e.g., age of acquisition of each language, how much exposure in each language, the context of language learning) in order to more accurately describe associations between the bilingual environment and the development of memory and EF.

Limitations

Limitations of this study include the small sample size. In particular, only a relatively small subset of infants in the present study were classified as bilingual language learners. This likely contributed to a lack of statistically significant differences when comparing frontal alpha power of bilingual versus monolingual infants. An additional cohort of individuals will be included as part of this project, however these additional data were not available at the time of preparation of this thesis. The present project represents an important first step in exploring questions related to neural development underlying EF in different language learning groups. Analyses presented here will be followed up in a larger sample. Another limitation is the measurement of bilingual status; considerable evidence suggests that bilingualism should be thought about and analyzed as a continuum of experiences as opposed to a distinct group separate from monolingual language learners (e.g., Anderson et al., 2018). While we were able to capitalize on a rich longitudinal dataset of infants experiencing low-SES, the original study was not designed to test questions about the bilingual experience. We were therefore limited to a single question about languages heard in the home. As noted, it would be helpful to include other factors to better quantify the bilingual experience, such as the age of acquisition and the amount of exposure to each language. In addition, for SES, since family income data was missing for a large number of participants, I was limited to using neighbourhood poverty as a proxy. While neighbourhood poverty isn't an equivalent measure of participants' individual income, it does provide important information about the economic context of families, and has been reported as a predictor of developmental outcomes in prior studies (e.g., Pierce et al., 2019). Nonetheless, subsequent studies should assess family income in a manner that lends itself to less missingness on this variable, which would allow for exploration of the unique contribution of each of these variables on neurodevelopmental outcomes. Finally, EEG was recorded in this study during baseline, which was used as an indicator of later EF. As a future direction, it would be ideal to also record EEG during an EF-related task. In the near future, I plan to run a study that measures preschoolers' alpha power during an EF task called the Day Night Stroop Task, which is a version of the classic Stroop task of inhibitory control, modified for use with young children.

Conclusion

Despite these limitations, this study demonstrated novel associations between SES variables - particularly rates of neighbourhood poverty - and frontal alpha power - an early neural predictor of EF. Associations were observed during infancy, suggesting an avenue to track early development of EF before behavioural challenges that are prevalent in children experiencing low-SES emerge. Moreover, preliminary evidence suggests a potential protective role of bilingualism on the development of early frontal alpha oscillations in a low-SES context. Further testing with a larger sample of bilingual participants will help to inform and validate this claim.

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